Power Dissipation of Embedded Resistors

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Abstract
Increasing component density and the requirement for high performance electronic devices are driving the development of electronic systems with passive devices, especially resistors, embedded in both printed circuit boards and chip carriers. A recent innovation, where a thin film NiCr alloy resistive layer is sputtered onto rolls of copper foil, is one of the materials for embedded resistor applications. NiCr alloys possess high electrical resistivity, good electrical performance and high thermal stability. The selective etchability of NiCr alloys facilitates fabrication into embedded resistors. To enable high performance devices, an embedded resistor must meet certain tolerances and power ratings. The design of embedded resistors and printed circuit boards has a strong influence on the resistor tolerance and power dissipation ability of embedded resistors. Our experimental and FEA simulation results show that the power dissipation ability of an embedded resistor is determined by the resistor size, shape and the particular printed circuit board structure. These results can be used as design guidelines for embedded resistors.

Introduction

Increasing component density and the requirement for high performance electronic devices are driving the development of electronic systems with passive devices, especially resistors, embedded in both printed circuit boards and chip carriers. A recent innovation, where a thin film nickel-chromium (NiCr) alloy resistive layer is sputtered onto rolls of copper foil, is one of the materials for embedded resistor applications[1]. NiCr alloys possess high electrical resistivity, good electrical performance and high thermal stability. The selective etchability of NiCr alloys facilitates fabrication into embedded resistors.

To be used in high performance devices, an embedded resistor must meet certain tolerances and power ratings, which are strongly affected by the design of embedded resistors and printed circuit boards. In our previous paper [2], we have discussed how the resistor size and resistor forming process affect the final resistor tolerance. In this paper, we present our experimental and finite element analysis (FEA) simulation results on the power dissipation ability of embedded resistors. The power dissipation ability of an embedded resistor is mainly a thermal management issue. It is strongly dependent on the resistor size, shape, the material of the printed circuit board and its surroundings because all of these factors will affect the heat dissipation of the embedded resistor. These test and simulation results can be used as general design guidelines for embedded resistors.

Power dissipation tests of thin film resistors

To understand the effect of resistor size on power dissipation, two sets of experiments have been done on thin film resistors. One test measures burnout power for a thin film resistor and the other measures the resistance change of a thin film resistor under different power loads.

The sample panels for burnout power test were 100 ohms/sq NiCr TCR™ resistive foil laminated on 5 mil FR4 prepreg. The resistors were 200, 500, and 800 μm wide and of various lengths. There was no copper cladding on the back of the laminate. The resistors were not embedded. The test was conducted at ambient temperature using natural air convection cooling. A constant current was applied to the resistor and the current was slowly ramped up from zero to a point the resistor burned out due to thermal decomposition of the underlying FR4 laminate material, destroying the resistor. The current which caused the resistor burnout was recorded as the burnout current, I_b, and the burnout power density P_b was then calculated by Equation 1,

$$P_b = I_b^2 R / A, \qquad (1)$$

where R is the resistance and A is the area of the resistor. The burnout current versus resistor size is plotted in Figure 1. It can be seen that the thermal dissipation ability of the thin film resistor is dependent on the width and length, and in turn depends on the size of the resistor. The narrower the width and the shorter the length, the higher the burnout power density will be because of the shorter heat conduction path to the surroundings. For a 200 μm wide resistor, burnout is observed at a power density as high as 1800 mW/mm^2. As the resistor size increases, the burnout power density drops, although the total power increases because of the larger resistor size, indicating that the relationship between the total power dissipation and the thin film resistor size is not linear. It was found that the resistor should be operated at a power level of no more than 20–30%

Paper presented at IPC Printed Circuits Expo 2003, Long Beach, CA, March 23 – 27, 2003.

of the burnout power value to keep the resistor temperature low with no significant change in resistance.

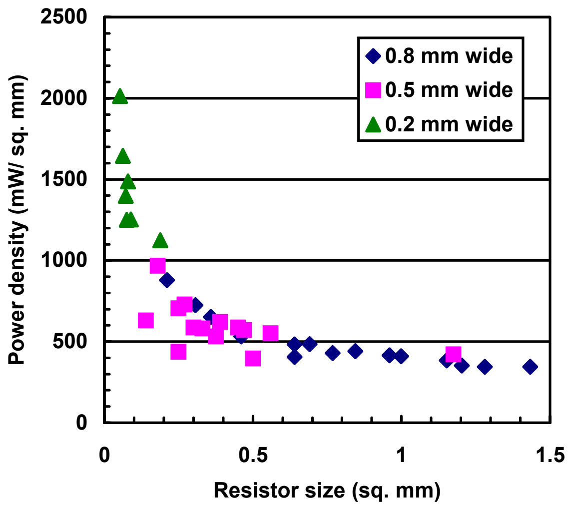


Figure 1: Burnout power of thin film NiCr resistor

The resistance change of thin film resistors under power load was also tested. The test resistor size was 30 mil by 30 mil laminated on one side of a 5 mil thick FR4 board. The resistors were not embedded. Both NiCr and nickel-chromium-aluminum-silicate (NiCrAlSi) resistor material were evaluated. A constant power was applied to the test resistors for one hour. As the power loading increased, the temperature of the thin film resistors increased, which in turn caused the resistance to change. The resistance before and after one hour current load was recorded. The resistance change at different power densities calculated from the current load and the size of the resistor is shown in Figure 2. Again, the test was conducted at ambient temperature, and there was no additional cooling except for natural convection.

As the current increases, or the power increases, the resistor temperature increases, which in turn, causes resistance change. As the resistor's temperature increases, the resistance of NiCr resistors also increases. Since NiCr has a negative thermal coefficient of resistivity, this is an indication that other factors are contributing to the observed change. Thermal expansion of the substrate is one such factor, as it was noted that the resistance of NiCr resistor decreased after heat treatment. It can be noted that NiCr exhibited higher resistance change than that of NiCrAlSi at the same power level, indicating that NiCrAlSi is more thermally stable than NiCr. It was also found that the resistance values had nearly returned to the original values after the applied current was turned off and the resistor cooled down.

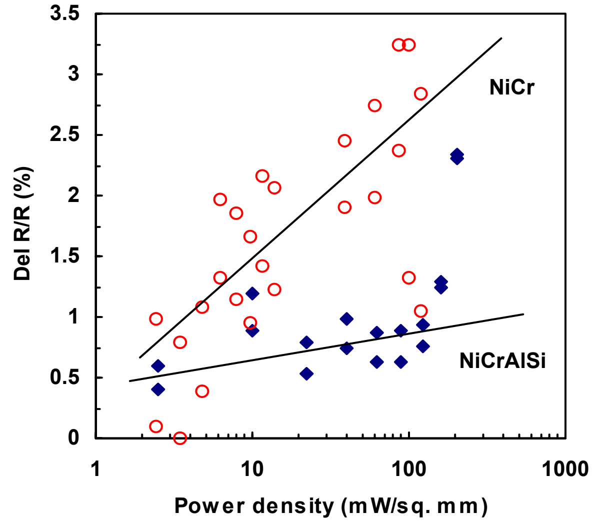


Figure 2: Resistance changes under power load, Resistive foil was laminated on single side of FR4 prepreg and the resistor size is 30 mil x 30 mil.

Finite element thermal analysis of embedded thin film resistor

To further understand the effect of resistor size, laminate core thickness and the presence or absence of external copper cladding on resistor temperature, thermal simulations were performed using finite element analysis (FEA).

The model used for the simulation is shown in Figure 3. Six resistor sizes were studied: 10 x 10, 30 x 30, 60 x 60, 120 x 120, 250 x 250, and 500 x 500 mil. In each case 10mil wide copper leads were present on each side of the resistor. All copper was 18 μm in thickness (1/2 oz). The resistors were sandwiched between two layers of FR4 epoxy/glass cloth PWB material. Eight different FR4 core thicknesses were evaluated: 5, 7.5, 10, 15, 20, 31.25, 40, and 62.5 mils. The board size was 6 inches long and 3 inches wide. It was assumed that the board was initially at ambient temperature and that free air convection cooling was present on each side of the board. A convection cooling coefficient of 5.5 W/m^2K was used. The other material properties used in model are listed in Table 1.

Table 1: Material Properties Used For Finite Element Thermal Analyses

Material	Electrical Resistivity (Ω-cm)	Thermal Conductivity (W/mK)
Resistor (NiCr)	0.016	70
Copper	1.672×10^{-6}	393
FR-4	1.5×10^{17}	0.2

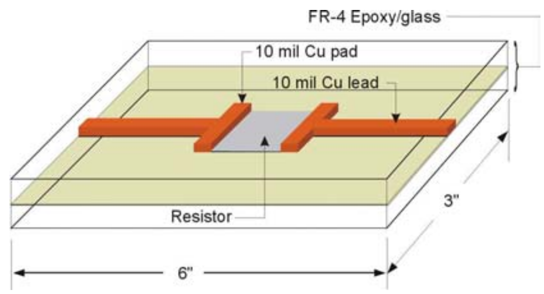


Figure 3: Embedded Resistor Thermal Model Geometry

Since the temperature distribution of a thin film embedded resistor is not uniform, the hottest spot is usually located at the center of the resistor for a non-trimmed bar shaped resistor. Figure 4 shows the relationship between maximum temperature and power density. Points indicating 5, 20, and 35 mW power are noted on the curves. It is clear that the smaller size resistors have much better power handling capability in terms of the power density. When operated at equivalent power density, the smaller resistors produce the smallest temperature rise. Although the small size resistor has better power handling capability, it handles less total power compared to larger resistors. The simulation results also show that in general, the resistor's temperature increases linearly as power increases.

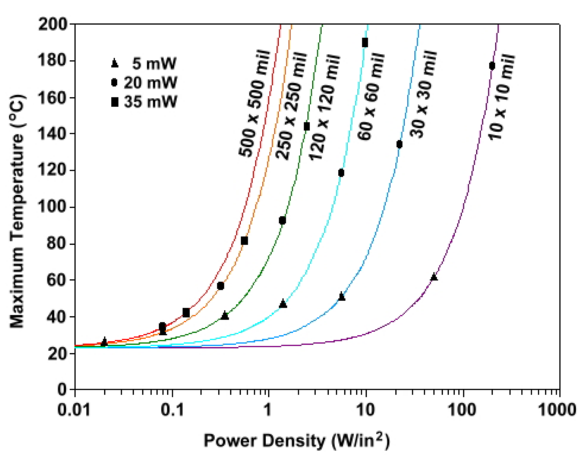


Figure 4: Maximum Temperature as a Function of Power Density for 500 Ω Embedded Resistors (5 mil core thickness, unclad model)

Figure 5 shows the effect of copper cladding on the maximum temperature of the resistors. The curves in Figure 5 are shifted to the right compared to the curves in Figure 4, indicating lower operating temperatures at equivalent power density for the clad laminates as compared to the corresponding unclad models. In general, the copper cladding on the backside of embedded resistor reduces the temperature of embedded resistors, especially when the copper cladding size is much larger than the size of the resistor because it will effectively increase the cooling surface area. However, when the copper cladding size is small or comparable to the size of the resistor, the effect may not be substantial and heat dissipation is primarily controlled by heat transfer from board to surroundings by free convection.

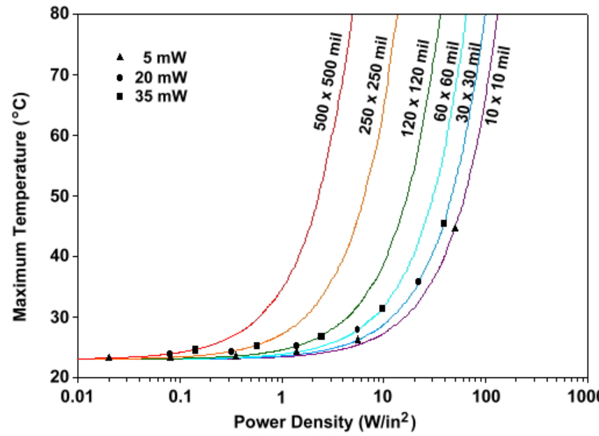


Figure 5: Maximum Temperature as a Function of Power Density for 500 Ω Embedded Resistors (5 mil core thickness, 1/2 oz. Copper cladding on one surface of laminate)

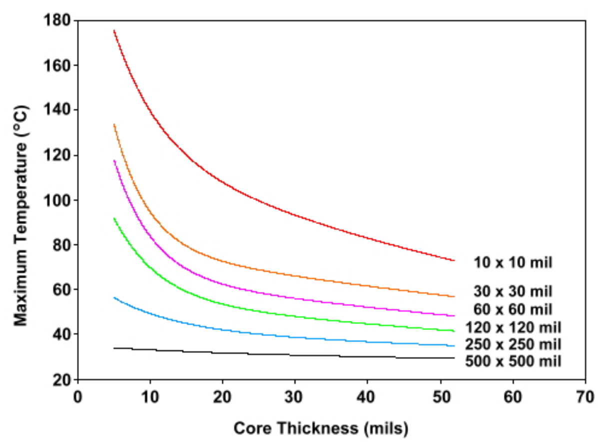
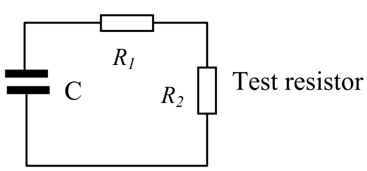


Figure 6: Maximum Temperature vs. Core Thickness for 500 Ω Resistors (20 mW power; unclad)

Figure 6 shows the effect of core thickness on the maximum resistor temperature. It is interesting that the temperature decreases significantly as the core thickness increases, which is contrary to our expectation that a thicker core would impede heat transfer. However, it is reasonable considering the higher heat transfer rate by conduction in an epoxy resin/glass material compared to the relatively inefficient heat transfer resulting from free convection at the board surfaces. Therefore, the heat transfer rate by surface convection to the surrounding environment determines the resistor temperature. When the core size is much larger than the size of the resistor, the simulation results show that the resistor on thicker core has a lower temperature than on a thinner core, indicating that thicker core provides larger effective cooling surface. However, if the core size is small or comparable to the size of the resistor, the effect of core thickness should not be significant.

Thermal dissipation of thin film embedded resistor at ESD test

Electrostatic discharge (ESD) test performance of a thin film resistor is also a thermal issue. The ESD (HBM - Human Body Mode) test simulates electrostatic discharge by charge carrying personnel coming into direct contact with resistors. During an ESD test, a certain amount of electric charge is discharged into the test resistor in a very short time (< 1 µs). During such a short time, only a very small amount of the heat generated by the test resistor can be transferred to its surroundings. Therefore, the majority of the heat generated has to be absorbed by the test resistor, resulting in a sharp temperature rise of the test resistor. The maximum temperature rise can be calculated by Equation 2, which assumes all the heat is absorbed by the test resistor:



$$\Delta T = \frac{q}{mC_p} = \frac{V_0^2 R_2 C}{2(R_1 + R_2)(w \cdot l \cdot d)\rho C_p} \qquad (2)$$

where
V_0: ESD test voltage, Volts
R_1: Current limiting resistor, ohms, (330 ohms)
R_2: Test resistor, ohms
C: Discharge capacitor, F (150 pF)
ρ: Density of resistive material, g/cm^3
C_p: Heat capacity of resistive material, J g^{-1} K^{-1}
w: The width of the test resistor, cm
l: The length of the test resistor, cm
d: The thickness of the test resistor, cm

Equation 2 shows that the temperature rise is a function of the heat capacity of the resistive material, resistor area and the resistor thickness. For a given resistive foil (sheet resistance, material), the heat capacity and the thickness of the resistive material are fixed. The ESD performance of an embedded resistor will depend only on the resistor size. The larger the area of the resistor, the higher will be the electrostatic voltage the resistor can handle. Thicker resistive material will be able to withstand higher voltages than thinner material.

We have conducted EDS tests for thin film resistors made of TCR™ resistive foil. The sample resistor sizes ranged from 10 x 10 mils to 125 x 125 mils. The test standard used was the Human Body Mode ESD test (IEC 61000-4-2), which used a 150 pF/330 ohms discharge network. One 2000 V pulse was discharged through each resistor. The resistance change before and after discharge was measured. The average resistance changes after one 2000 V pulse discharge are listed in Table 2. The average resistance change value was calculated by excluding broken resistors (if any) in the group. The number of failed resistors and passage rate are listed in Table 3. The criterion for a failed resistor was a resistance change larger than ±5% after discharge.

The data in Table 2 and Table 3 tell us that the ESD test is a severe and very destructive test for embedded thin film resistive material due to the small mass of the thin film resistive material. At the 2000 V discharge level, only large size resistors or resistors made from thick resistive material could survive the test. For small size resistors, it was found that the resistive material had completely vaporized after the 2000 V discharge. Decreasing discharge voltage will significantly reduce the test severity and enable small size resistors to pass the test. An illustrative plot of the relationship between the survivable discharge voltage and the minimum resistor size is shown in Figure 7. NiCrAlSi performs better than NiCr because NiCrAlSi is thicker than NiCr for the same sheet resistance. The ESD performance of resistors improves slightly after the resistors are embedded. The test results confirm that the temperature rise is a function of the heat capacity of the resistive material, resistor area and the resistor thickness.

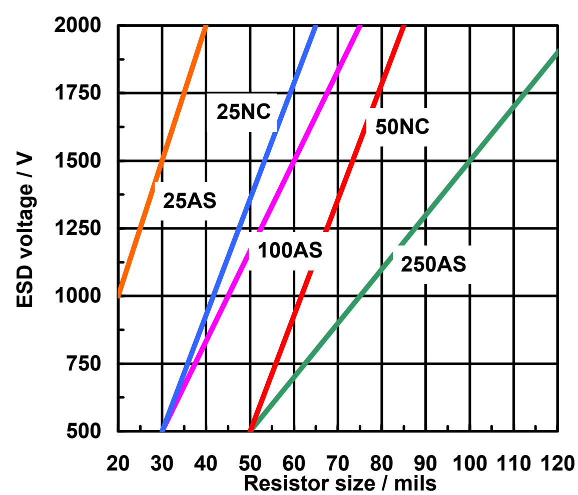


Figure 7: An illustration plot of the minimum resistor size to pass ESD test

Conclusions

The power dissipation ability of a thin film resistor is a heat management issue. In general, increasing the size or area of a thin film resistor increases its total power handling ability. However, the relationship between the total power dissipation and the thin film resistor size is not linear because in terms of the power density, the power dissipation ability of a thin film resistor decreases as its size increases. Thin film resistor performance in ESD testing is also a thermal issue. The total mass of the resistive material is a key factor in determining the temperature rise of the resistor due to the discharge. A greater mass (thicker film or larger resistor size) significantly reduces the thermal shock during the test. Since the resistive layer thickness for thin film resistors is about 100–1000Å, the ESD test is very severe and destructive. For a given resistor thickness or sheet resistance, increasing the resistor size seems to be the only way to reduce ESD failure. However, when limited space precludes the use of larger size resistors, protection at the circuit level may be required. Finally, it should be pointed out that the results presented in this paper were obtained based on specific test circuits or simulation models. The results should only be used as general design guidelines for embedded resistors.

References

1. J. Wang and S. Clouser, IPC EXPO 2001 Proceedings of the technical conference, "Thin film Embedded Resistors", S08-1, April, 2001.
2. J. Wang, R. Hilburn, S. Clouser and B. Greenlee, IPC EXPO 2002 Proceedings of the technical conference, "Manufacturing Embedded Resistors", S03-4, November, 2002.

Table 2: Resistance change after one pulse of 2000V discharge (150pF/330ohms network)

Before embedded

size, w x l	25AS	100AS	250AS	25NC	50NC	100NC
125x125	0.00	-0.73	-0.90	-0.40	-1.02	0.17
80x80	-0.06	-1.40	-1.05	-1.54	-2.50	0.62
60x60	-0.17	-2.13	4.89	-2.36	-3.94	0.59
50x50	-0.33	-	-	-3.66	-4.89	0.45
40x40	-0.12	-	-	-5.09	-6.49	-
30x30	-1.27	-	-	-7.80	-8.57	-
20x20	-1.65	-	-	-12.14	-	-

After embedded

size, w x l	25AS	100AS	250AS	25NC	50NC	100NC
125x125	0.00	-0.66	0.60	-0.39	-0.68	-0.08
80x80	-0.01	-1.58	-0.78	-0.94	-1.77	-0.30
60x60	-0.02	-2.36	-	-1.81	2.75	-0.63
50x50	-0.06	-2.67	-	-3.09	-3.56	-0.37
40x40	-0.18	-3.06	-	-3.84	-4.82	-
30x30	-0.46	-	-	-5.25	-6.07	-
20x20	-0.91	-	-	-8.36	-	-

Table 3: Resistor failure and pass rate after one pulse of 2000V discharge (150pF/330ohms network)

Size, w x l	Total	25NC		50NC		100NC		25AS		100AS		250AS	
mil x mil		# F	% P	# F	% P	# F	% P	# F	% P	# F	% P	# F	% P
125x125	12	0	100	0	100	0	100	0	100	0	100	0	100
40x240	12	0	100	0	100	0	100	0	100	3	75	6	50
80x80	12	0	100	0	100	1	92	0	100	0	100	1	92
40x160	12	0	100	0	100	4	67	0	100	4	67	12	0
20x240	12	0	100	1	92	6	50	0	100	3	75	8	33
60x60	12	0	100	2	83	1	92	0	100	0	100	2	83
20x160	12	0	100	1	92	6	50	1	92	9	25	11	8
40x80	12	0	100	2	83	9	25	0	100	6	50	10	17
50x50	12	1	92	4	67	1	92	0	100	1	92	3	75
40x40	24	14	42	21	13	11	54	3	88	8	67	16	33
20x80	12	0	100	5	58	12	0	2	83	10	17	12	0
30x30	12	11	8	12	0	6	50	0	100	11	8	12	0
20x40	12	9	25	12	0	12	0	3	75	12	0	12	0
40x20	12	9	25	11	8	4	67	1	92	11	8	12	0
20x20	24	22	8	24	0	24	0	1	96	24	0	24	0
40x10	12	10	17	11	8	12	0	3	75	12	0	12	0
20x10	12	12	0	12	0	12	0	3	75	12	0	12	0
10x10	12	12	0	12	0	12	0	8	33	12	0	12	0
Total # F	240	100		130		133		25		138		177	

Resistors are embedded

Size, w x l	Total	25NC		50NC		100NC		25AS		100AS		250AS	
mil x mil		# F	% P	# F	% P	# F	% P	# F	% P	# F	% P	# F	% P
125x125	6	0	100	0	100	0	100	0	100	0	100	0	100
40x240	6	0	100	0	100	3	50	0	100	0	100	0	100
80x80	6	0	100	0	100	0	100	0	100	0	100	0	100
40x160	6	0	100	0	100	2	67	0	100	2	67	1	83
20x240	6	2	67	0	100	3	50	0	100	1	83	0	100
60x60	6	0	100	1	83	0	100	0	100	0	100	1	83
20x160	6	0	100	0	100	1	83	0	100	1	83	2	67
40x80	6	2	67	0	100	1	83	0	100	2	67	4	33
50x50	6	3	50	0	100	0	100	0	100	0	100	2	67
40x40	12	5	58	6	50	3	75	0	100	1	92	6	50
20x80	6	0	100	0	100	2	67	0	100	3	50	5	17
30x30	6	3	50	5	17	2	67	0	100	3	50	3	50
20x40	6	2	67	5	17	3	50	0	100	2	67	6	0
40x20	6	3	50	6	0	3	50	0	100	3	50	6	0
20x20	12	7	42	12	0	9	25	0	100	9	25	12	0
40x10	6	6	0	6	0	6	0	0	100	5	17	6	0
20x10	6	6	0	6	0	5	17	0	100	6	0	6	0
10x10	6	6	0	6	0	6	0	0	100	6	0	6	0
Total # F	120	45		53		49		0		44		66	